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GRAN EXPERIMENT

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MARCH 1973

GSFC GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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I. EXPERIMENT MOTIVATION

The motivation of the Coast Guard and the Navy, as well as other SAR agencies, in seeking a GRAN system, is a documented recognition of the human and economic costs associated with long searches for disaster survivors. It is believed that its implementation will materially assist in decreasing fatalities, injuries and property losses due to transportation-related accidents and in increasing the cost/effectiveness of search forces.

The most significant factor in effecting a successful SAR effort is reducing the delay in notifying the rescuing agencies. The average delay experienced has been from 5.6 to 7.5 hours. Even in the best of climatic conditions, such a hiatus in relief operations carries critical penalties for safety. By shortening this time, fewer lives would be lost due to exposure, drowning or untreated injuries. It has been estimated that such a system could conservatively save 425 lives in the United States each year. Extrapolating the figures to world-wide coverage would mean a commensurately higher total.

The need for GRAN cuts across the boundaries of all transportation modes. On the one hand, spectacular incidents occur with sporadic frequency. The SS TEXACO OKLAHOMA sank on March 27, 1971, with 38 crewmen perishing in the aftermath and potential rescue agencies completely unaware of the event until four days later. In the ensuing 11 days of fruitless searching, 72,000 square miles of ocean were examined by 6 Coast Guard vessels, 20 aircraft of the Coast Guard, Air Force and Marine Corps, and 7 tankers of the Texaco fleet. On the other hand, in individual incidents, lives are lost on almost a daily basis throughout the nation.

A typical year will find the Coast Guard responding to some 34,000 separate SAR incidents requiring assistance to vessels, with about 1600 fatalities. Although GRAN will not eliminate these deaths, it can serve to diminish the number.

Light Civil aircraft form a category of transportation with definite hazards and a great potential for a GRAN solution. The Air Force Aerospace Rescue and Recovery Service annually searches for some 100 light aircraft and locates nearly 90% of them. However, 57 aircraft which crashed in the Continental United States during the period 1961-1967 have never been found. Over-water flights, of course, are more unpredictable and a higher incidence of distress location difficulty is evident.

The economic impact of GRAN is expected to benefit SAR forces and the distressed units. For the distress units, the gain cannot be easily quantified. It is known that the Coast Guard annually saves some two billion dollars in property damage by timely and effective action in SAR incidents. If this amount were increased by a conservative 10%, enough would be gained in a single year to pay for the GRAN space segment and a sizeable number of Search and Rescue communicators (SARCOM) for mobile users.

Nor is this the total cost impact. Real and significant operating savings will accrue to SAR forces in reduced search costs. A SAR simulation model which closely parallels the GRAN concept has postulated that the search could be done for 2% of the direct costs and with only 4% of the required time as compared to a visual search. It may be of interest to note that the visual search costs would purchase approximately 10,000 SARCOMs at a unit cost of $200 each for the hypothetical SAR mission.

In recognition of the need for GRAN concepts, many organizations have firmly supported its development. The Inter-Governmental Maritime Consultative Organization (IMCO), which is the specialized agency of the United Nations dealing with maritime subjects, has cited an operational requirement for the "use of low-power emergency radio beacons to enable survivors to alert rescue coordination centers" using satellites. The International Civil Aviation Organization (ICAO) is actively examining their needs for space services but have not yet identified this requirement. However, the general concept of SARCOM (nonsatellite) is strongly supported by aviation interests. The Federal Aviation Administration (FAA) will require most general aircraft (some 130,000 in the United States) to carry crash locator beacons after 1973.

The Air Force through its Survival Avionic's Life Support System program has established in conjunction with the Navy and Army, a triservice study to determine the optimum search and rescue system. The requirements of their study detailed in Specification F33657-71-R-0538 call for a SAR avionics package consisting of two units: a Distress Incident Locator (DIL) and a Survivor Locator Group (SLG). The DIL shall provide at a central location aircraft identification and aircraft location. The SLG will provide precise location in the range of from 2 to 10 miles to 25 ft. The triservice study, performed by two independent contractors, recommends a GRAN type system using Advanced OPLE techniques. The studies have assumed that GRAN type experimentation will have been completed by 1975 in order to incorporate those results into a system for military users.

The commitment of the Coast Guard and Navy are well-known and backed up by their participation in this experiment. In the collective view of SAR agencies, GRAN offers the chance to bring modern technology to bear on the age-old problem of safety of life at sea, in the air or on the ground.

II. INTRODUCTION

The NASA OPLE concept evolved from a desire to establish global location and to collect data from remote platforms on a real-time basis for scientific investigation of natural phenomena in meteorology, oceanography, etc. NASA successfully demonstrated the concept in 1968 using the ATS-1 and -3 satellites to perform experiments with balloons, buoys and land deployed platforms. This accomplishment was also significant in that it opened new horizons in research and applications which could be achieved through improvement of the ATS/OPLE system. Accordingly, an Advanced OPLE system study was initiated under the NASA/Goddard Supporting Research and Technology Program.

As a result of these efforts, the Naval Air Test Center (NAVAIRTESTCEN) recognized the potential of the OPLE concept for application to worldwide rescue of survivors. The important advantages of the system are its real-time features and utilization of a minimum number of satellites. In 1970 NAVAIRTESTCEN carried out tests using borrowed NASA/OPLE equipment and facilities which were modified for UHF operation. These tests established the feasibility of using the OPLE concept to design a GRAN which reduces the time between a mishap and rescue attempt from hours or days to minutes. The tests are well documented and resulted in the following specific recommendations:

a. Continue to develop the GRAN concept with appropriate speed and resources.

b. Develop and test techniques for resolution of Omega lane ambiguity problem.

c. Refine the Exalted Acquisition/Reference (A/R) technique (low power tone acquisition) to obtain the most economic power budget consistent with desired reliability.

d. Conduct experiments to demonstrate methods for instantaneous skywave corrections for improvement of localization accuracy.

e. Develop a small hand held emergency transceiver "SARCOM" for test and evaluation.

These goals are synonymous with those established under the Goddard Space Flight Center (GSFC) Advanced OPLE Program.

Thus, the development of the GRAN system could be efficiently pursued by integrating respective efforts of NASA and NAVAIRTESTCEN under a joint flight program. The GRAN concept would be advanced to the point where final specifications of a semioperational system could be formulated.

The U.S. Coast Guard has statutory responsibility of developing, establishing, maintaining and operating rescue facilities for the promotion of safety on and over the high seas and waters subject to the jurisdiction of the United States. Under this mandate, it became interested in the NASA and NAVAIRTESTCEN work, endorsed the goals, and sought to bring the GRAN concept to an operational stage. Accordingly, the Coast Guard was instrumental in obtaining a frequency allocation for the system at the 1971 World Administrative Radio Conference for Space Telecommunications (WARC-ST) and will cooperate with GSFC and NAVAIRTESTCEN in the GRAN experiment and with other SAR agencies in pursuing the operational aspects of a future system.

The development of an Advanced OPLE concept will also offer a capability for other user applications. It is anticipated that interest will be solicited among data collection users for additional experiments. The U.S. Naval Oceanographic Office has a requirement for real-time buoy tracking experiments to improve ocean current forecasting techniques. Interest has also been expressed by scientists in meteorology and ecology for real-time data gathering systems.

III. EXPERIMENT DESCRIPTION

The principal objective of the GRAN experiment is to solve the acute problem facing the various SAR agencies in reducing the time lost between a mishap and rescue efforts from hours or days to just minutes. The lifesaving goal will be advanced by demonstrating Advanced OPLE techniques which meet SAR requirements in terms of reliability, accuracy and ultimate user cost. In so doing, the time consuming and costly Search phase will be practically eliminated from future Search and Rescue missions.

A secondary objective is to gain much needed practical experience in the efficient management and operation of a worldwide SAR system under real-time conditions. It is anticipated that much will be learned regarding real world considerations in the disposition of men and equipment for such emergencies.

The experiment will consist of system technical evaluations and simulated SAR missions. The technical evaluations will consist of test sequences wherein platforms, situated at known sites, will be operated under "worst case" conditions for total system assessment. Simulated Search and Rescue missions will serve to demonstrate system features. Ten platforms are required to obtain sufficient statistics of simultaneous transmissions from the test regions selected. For example, if the satellite were located at 105°W Longitude, the typical sites might be the following:

1) Fairbanks, Alaska
2) Midway Island
3) Samoa
4) Thule Air Base, Greenland
5) Antarctic Peninsula
6) Equatorial jungle
7) U.S. inland lakes
8) U.S. desert

Near each of the above sites sufficient manpower and facilities exist to provide needed support, and most sites are serviced by the Military Airlift Command. Geographically, the regions encompass the satellite coverage area in both hemispheres, thus providing a wide range of atmospheric and terrain conditions. Details of the experiment are described below.

A. TECHNICAL EVALUATION

1. Deploy platforms throughout the field of view of the satellite. Selection of sites will be based upon the following:

    a. Combinations of "worst" and "best case" conditions for VLF and UHF frequency characteristics.

    b. Omega lane geometry and relative distance from transmitters.

2. From each selected site the following tests and evaluations are to be performed:

    a. Ability of system to meet an acceptable success rate in terms of alerting and location accuracy and false alarm rate. A successful test consists of receiving a transmission and computing position, within minutes, to the Omega system accuracy.

    b. Performance under various UHF Signal-to-Noise (S/N) ratios.

    c. Performance at reduced power levels to ascertain success ratios for each level.

    d. Verification of techniques for resolution of lane ambiguity through use of additional tones, multiple lines of position (recursive filtering), composite line of position correction for diurnal variations, time of arrival of the pulse, signal-to-signal measurement, and differential Omega.

e. Ability of system to receive and process four simultaneous alarm transmissions.

B. SAR EVALUATION

A field operation involving two mobile units will be carried out. Mobile units will travel to positions unknown to the central facility; each will initiate an alarm transmission. The message will be received, processed and communicated to rescue stations for simulated rescue missions. The intercept, or time to locate the survivor within the mishap area, will be logged along with other pertinent data relative to the rescue (weather conditions, etc.). These tests will include a mission covering up to 1500 miles (as in a mid-Atlantic mishap), and a remote area mishap in the region of the Rocky Mountains. The tests will be carried out with rescue aircraft or ships equipped with standard navigation equipment to insure accurate intercept courses. There will also be tests conducted using other navigation aids for comparison. A summary of the critical SAR statistics to be measured throughout these tests is as follows:

1. Alert/processing time
2. Communicating and dispatching SAR vehicles
3. Intercept time (actually spotting the distressed party)
4. Overall SAR mission time

A comparison will be made with existing statistical data from the United States Coast Guard (USCG), the Air Force Rescue and Recovery (ARRS), and the Naval Safety Center (NAVSAFCEN).

C. CONCLUSIONS AND RECOMMENDATIONS

Data from all phases of the experiment will be analyzed and areas of future study will be identified by the team of investigators. Of particular significance is the data on ambiguity resolution, which will result in recommendations to the Omega Steering Committee for changes, if any, to the present Omega format. Other areas in which conclusions and recommendations will be made include, but are not limited to, the following:

1. The effect of Radio Frequency Interference (RFI) on system performance.

2. A channelization scheme among the user population which meets requirements for an operational system in the 406-406.1 MHz band.

3. The need for multiple, narrow beam spacecraft antennas to permit increased user population and/or reduced power levels in the SARCOM.

4. The identification of a suitable frequency band for the link between ground station and satellite.

5. Preliminary plan for prototype GRAN system, including satellites and ground stations configuration.

IV. SYSTEM DESCRIPTION

A. BASIC SYSTEM CONCEPT

The GRAN concept, based upon an Advanced OPLE principle, is shown in Figure 1. The sequence proceeds as follows: 1) distress call is initiated by a survivor and consists of the retransmission of Omega tones and a unique identifying code (social security number), 2) signals are frequency translated through the satellite from UHF to SHF, and (3) the received signals are processed in real-time using improved skywave correction and lane ambiguity resolution techniques. The output results in geographical coordinates, time of day and unique ID. This information is then relayed to the closest rescue agent.

B. SATELLITE

The GRAN experiment, as described, will require a geosynchronous satellite equipped with an earth coverage antenna having a gain of at least 8 dB for any point on the covered portion of the earth. Alarm signals from the SARCOMs are received by the UHF antenna, frequency translated to an intermediate frequency and passed through a band pass filter having (ideally) a width of 100 KHz at the 3 dB point. The signals are then amplified in a linear amplifier with Automatic Gain Control (AGC), up-converted to SHF and frequency multiplexed (if necessary) with other wideband satellite sensor data. Because the SARCOM signals are narrow band (3.0 KHz) and only require a modest carrier to noise ratio (40 dB/Hz), the SARCOM signals, when multiplexed, may be as much as 20 dB below the wideband data without suffering appreciable degradation. Since the GRAN-unique satellite equipment is small, lightweight, and consumes little power, GRAN can readily share the satellite with other experiments or missions.

During eclipse the GRAN link could be supported with low power in the downlink even though a wideband link may have to shut down. The GRAN system power budget link calculations will assume that GRAN receives only a -20 dB share of

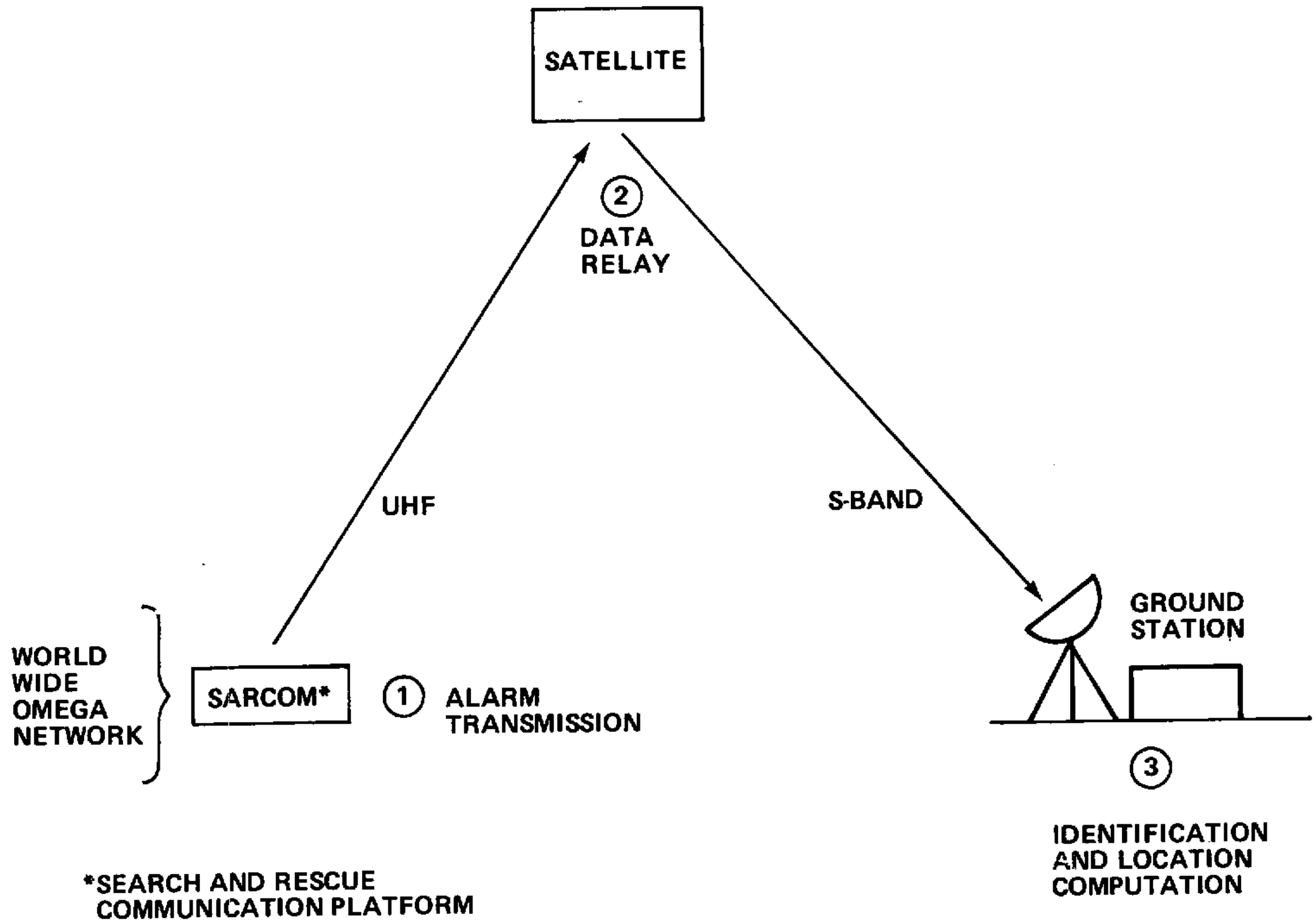

Figure 1. GRAN System Concept

available satellite downlink power in normal operation but that this same power level is available during eclipse. The link calculations are discussed below.

Operational Satellite System

The circle of illumination on the earth by an equatorial synchronous satellite has a radius of about 81 degrees of longitude at the equator. This circle is centered on the equator, and extends to within about 9 degrees of each pole. With two synchronous satellites in equatorial orbits spaced on opposite sides of the earth, the total coverage would include all but a 17 degree wide segment circling the earth, as illustrated in Figure 2a. With three synchronous satellites in equatorial orbits equally spaced around the earth, complete coverage is provided from about 73 degrees north latitude to 73 degrees south latitude. This coverage would extend to the arctic and antarctic circles (located at approximately ±66 degrees latitude) with a minimum platform-to-satellite elevation angle of about 7 degrees. The two spherical triangular areas, located at the poles, which are not covered are illustrated by Figure 2b. By using one synchronous satellite with an inclined plane, along with two synchronous satellites in the equatorial plane, coverage of each pole could be obtained for one continuous period of time each day. The length of this time period depends on the angle of inclination of the orbital plane to the equatorial plane. A plot of the pole visibility time in hours is given in Figure 3 for antenna elevation angles of 0, 5 and 10 degrees.

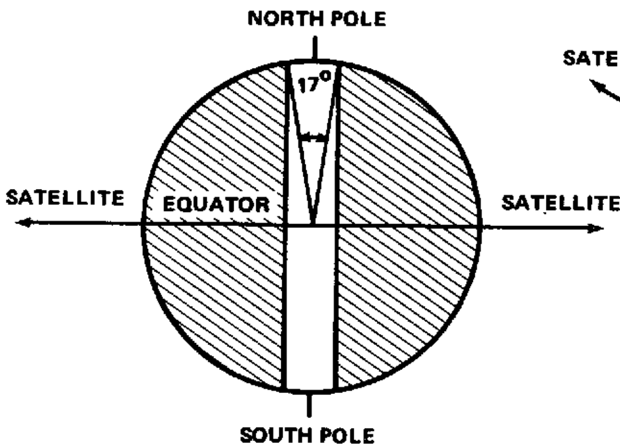

Figure 2a. Coverage by Two Equatorial Synchronous Satellites

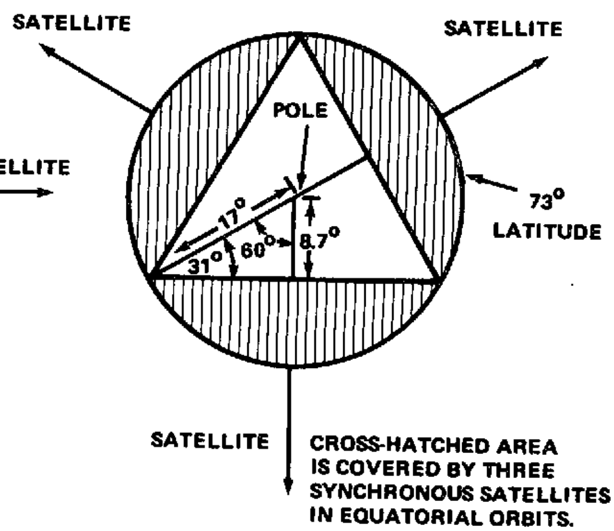

Figure 2b. Polar Blind Region for Three Equatorial Synchronous Satellites

Figure 2. Polar Coverage

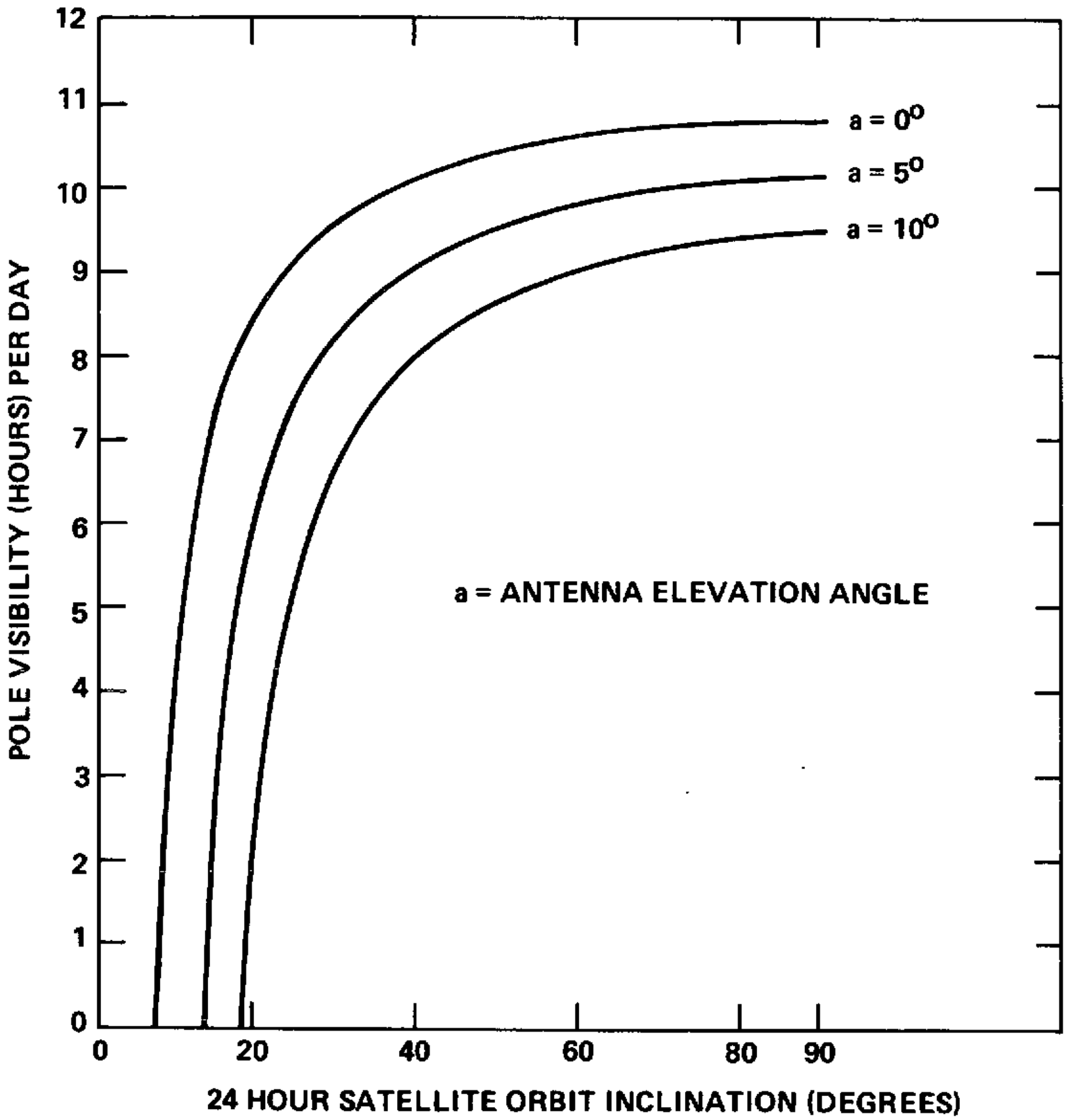

Figure 3. Synchronous Satellite Pole Visibility Time vs Orbital Inclination

The combination of three synchronous satellites properly phased, where one has an orbital plane inclined by 30 degrees would allow full earth coverage over each 24-hour period. The inclined plane allows the satellite to look over the poles and view the entire area not seen by the other two satellites. Each polar area would be entirely covered for a minimum of 4 hours per day. It seems that virtually any realistic operational requirement could be met by three phased synchronous satellites, each with properly selected inclination angles.

At synchronous altitude, the angle subtended by the earth is 16.4 degrees. This would allow use of an antenna with approximately 20.1 dB gain which would assuming zero pointing error, provide a minimum of 17.1 dB of gain over the entire illuminated area of the earth. An antenna pointing error of 25% (4.1 degrees) would necessitate using an antenna with a gain of 16 dB, which would provide a minimum gain of 13.7 dB over the illuminated area of the earth. Thus, the maximum allowable antenna gain is determined by the antenna pointing error, and since 4 degrees of error is well within the capability of present mechanical and electrical stabilization systems, a nominal 14 dB gain antenna is feasible for an operational system.

C. PLATFORM

The SAR communication platform (SARCOM) proposed for this experiment consists of a modification of the ATS/OPLE design to provide conversion to UHF and reduction in size, weight and power. The unit will not require an interrogation receiver since transmissions will be initiated at the SARCOM. A major objective is to provide a unit which can be hand held and provide approximately 30 minutes of operations, although not necessarily continuous broadcast.

Under the Advanced OPLE Program at GSFC, the feasibility of reducing the present platform volume and weight has been established through engineering studies. SARCOM package requirements call for the following:

Volume	50 in^3
Weight	2 lbs.
Output Power	5 W max.
Operation	3 minute broadcasts repeated at intervals, or one-time operation for 30 minutes
Data	Social Security Number (36 bits) or other unique identifier

These specifications will require use of miniaturization techniques. An effort has been initiated under the GSFC SRT program to demonstrate this feasibility. Platforms produced for the GRAN experiment will be based upon the designs developed under the GSFC program, and will be representative of user end item SARCOM.

In operation, platform transmission sequences consist of the following modes:

Mode 1. Acquisition Mode
Mode 2. Data Mode
Mode 3. Omega Mode

During the acquisition mode (Mode 1), the platform transmits an A/R tone at full power output. At the Control Center a Phase Lock Loop (PLL) receiver acquires the full power A/R tone.

During the data mode (Mode 2), digitized data phase modulates the A/R tone using ±60°PSK. The platform power output is therefore split between the sideband signal power resulting from the PSK modulation, and the A/R tone, on a 3:1 basis. At the Control Center, the PLL receiver assumes a narrow-band tracking mode (10 Hz) and continues tracking the received, reduced power, A/R tone. The output of the PLL receiver is routed to a PSK demodulator and the digitized identifier data extracted.

During the Omega mode (Mode 3), the three Omega tones, filtered VLF noise around each of the Omega tones, and the A/R tones share the output power. The spectrum is shown in Figure 4. The basic Omega tone-to-VLF Noise Power Ratio is chosen as 0 dB in a 1 Hz bandwidth. By centering the tones in 100 Hz filters, the platform output power is shared in accordance with Table 1.

Table 1

Output Power Sharing

Signal	Share of Output Power	
	%	dB
A/R Tone	10	-10.0
10.2 KHz tone and associated VLF Noise Power	30	-5.22
11.33 KHz tone and associated VLF Noise Power	30	-5.22
13.6 KHz tone and associated VLF Noise Power	30	-5.22
	100	

Throughout this transmission, the PLL receiver continues to track the received A/R tone, although the latter has now been even further reduced in power. The output of the PLL receiver is routed to matched 1 Hz filters, the output of which is integrated for 18 one-second samples, which results in an overall improvement in Omega tone-to-VLF Noise Ratio by a factor of 36. Since final position data is obtained by taking the difference between the transmission of two Omega tones of the same frequency but from two different Omega stations, the resulting improvement factor is 18.

A functional block diagram of the platform is shown in Figure 5. The basic elements consist of a VLF antenna and receiver, Omega tone filters, two local oscillators, and a UHF transmitter and antenna. The spectrum of the Omega signal is folded, as shown in Figure 4, to reduce separation between extremes of the baseband. This is achieved by dividing the local oscillator frequency and multiplying the received VLF signals in the common "band folding" technique. This technique allows frequency division multiple access while maintaining band integrity. Local oscillator F-2 is common to all platforms and is a multiple of the Omega tones. It is used to synthesize all mixing frequencies as well as the A/R tone. The second oscillator F-1 determines the platform channel assignment.

In operation, transmissions are initiated by the survivor; the present sequence then proceeds as follows:

Event	Time Interval
Transmit A/R tone (5.0 W) (Mode 1)	11.3 sec.
Transmit ID (Mode 2)	2.0 sec.
Resume A/R	2.0 sec.
Reduce A/R power (0.5 W)	2.0 sec.
Transmit Omega (Mode 3)	180.0 sec.
Total Time	197.3 sec.

The 15 second approximation for A/R tone transmission time is based upon received C/KT at the ground station to achieve 99% probability of phase lock. The actual time will be determined during the experiment study phase where various options and tradeoffs will be made. Threshold extension techniques will be investigated for possible reduction of acquisition time. The system margins are discussed later under link calculations.

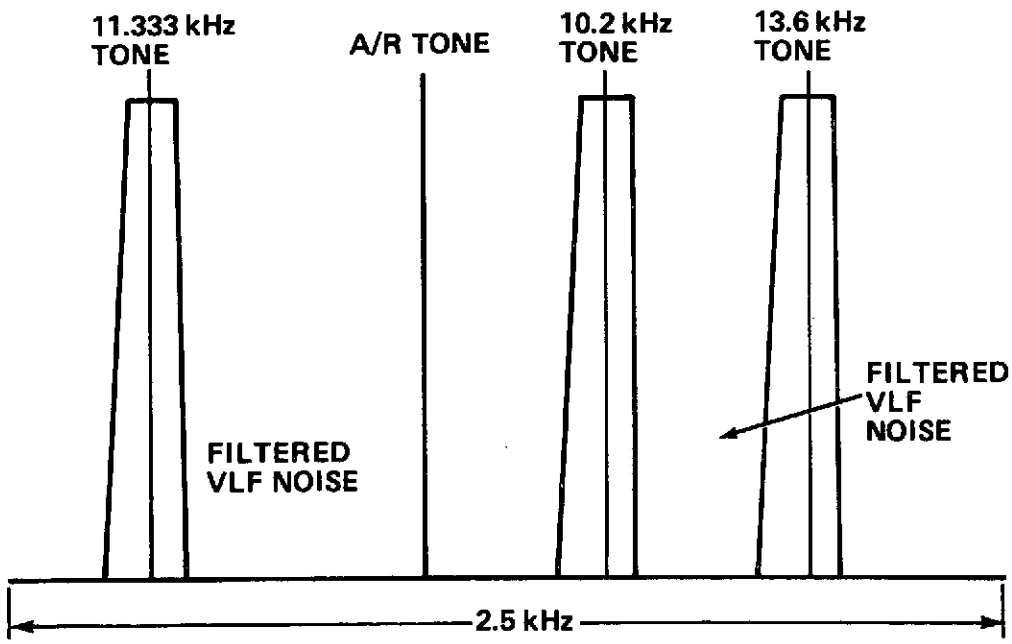

Figure 4. Folded OPLE Spectrum

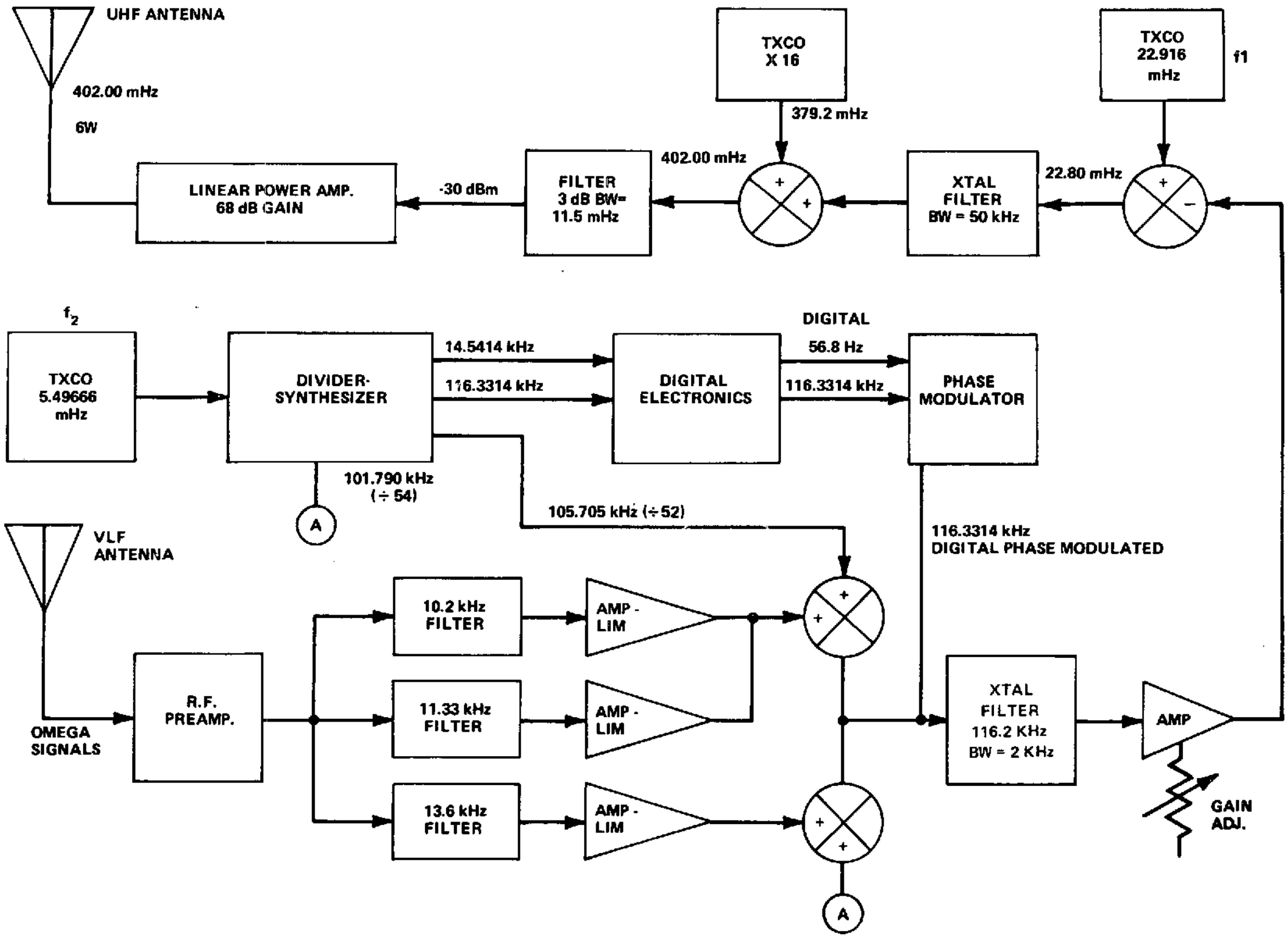

Figure 5. Block Diagram of SARCOM

D. GROUND STATION

The equipment used in the ATS/OPLE experiment, the OPLE Control Center (OCC), will be modified for compatibility with the synchronous satellite's ground facilities and SAR requirements.

Real-time processing of received data combined with ambiguity resolution of Omega lanes are the areas of prime importance to SAR, and will account for the majority of changes. At the present time, it is expected that enlargement of the computer capacity will satisfy the majority of requirements.

1. OCC Functions

The OCC performed six basic functions in the OPLE system; all but one will be used in the GRAN Experiment. First, it generated and transmitted platform interrogations to the satellite. This function will not be used with the GRAN Experiment. Second, it received, demodulated, and stored sensor data transmitted from the platforms to the OCC via the satellite. The GRAN SARCOM will send identification data instead of sensor data, but formatting will be similar. As its third function, the OCC received, demodulated, and processed the platform OMEGA data into the format required by the off-line computer for subsequent platform position determination. The GRAN Experiment proposes to process OMEGA data on-line using an enlarged computer capacity. Fourth, the OCC controlled the entire OPLE system operation, provided the required timing functions, and synchronized the OPLE system to the OMEGA Navigation System. The fifth function of the OCC was to simulate up to 40 OPLE platforms (useful but not essential to the GRAN experiment). Sixth, the OCC continuously monitored the status of the Omega Navigational System.

2. OCC VLF Data Processing Technique

By far the most critical function performed by the OCC is the processing of platform Omega data. This function can be separated into three basic tasks: (1) demodulation of the platform Omega tones, (2) measurement of the phases of these tones, and (3) compensation for frequency errors in the platform Omega data. A functional block diagram of the OCC Omega data processor is shown in Figure 6. As indicated, phase-locked demodulators accept the IF output of the receiver, phase-lock to the selected A/R tones, and demodulate the platform Omega tones. The outputs of each phase-locked demodulator are three low-frequency tones (426 Hz, 707 Hz, and 941 Hz) which represent the 10.2-kHz, 11.33-kHz, and 13.6-kHz platform Omega tones, respectively. Each platform Omega tone is then conditioned and applied to two identical synchronous

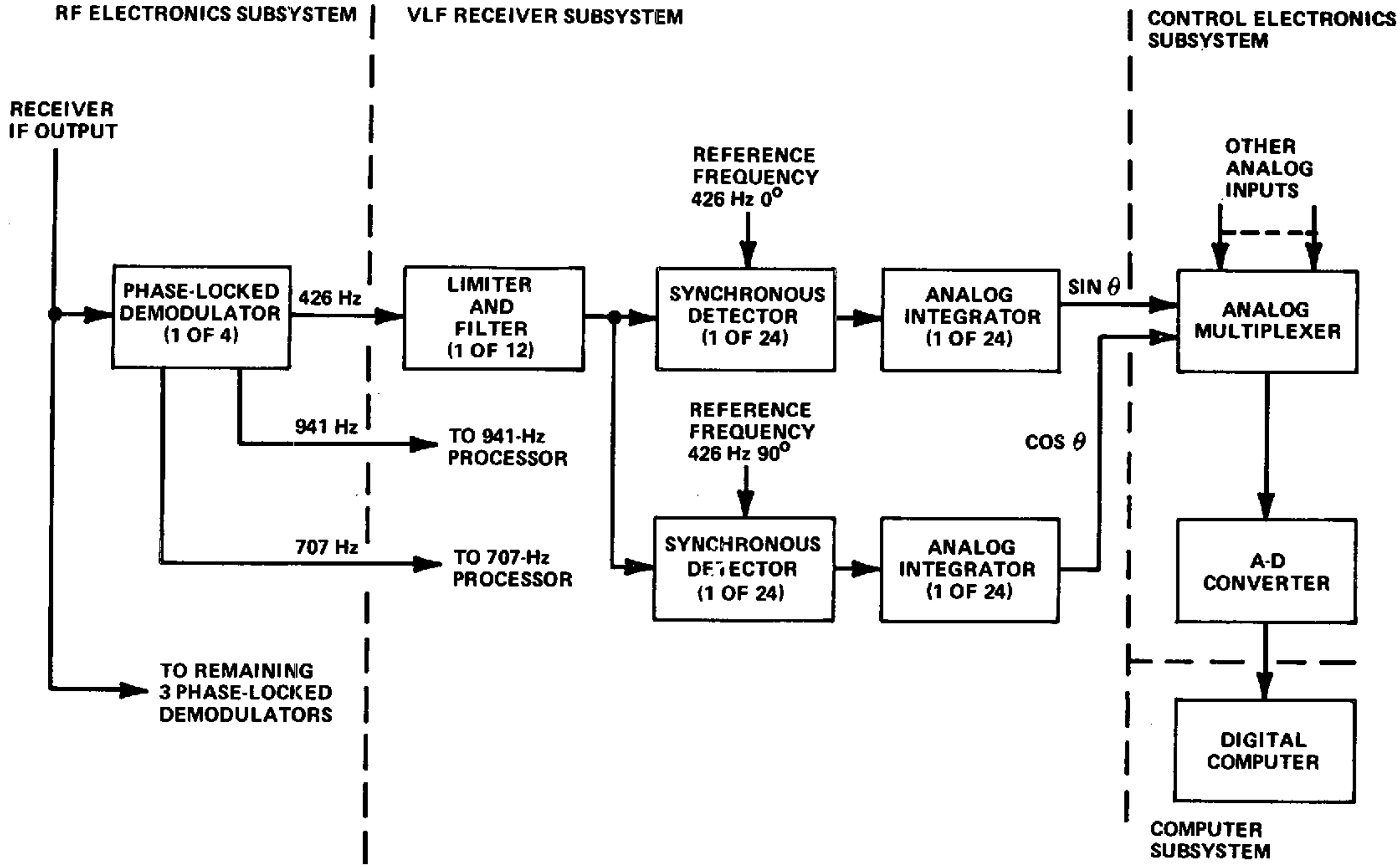

Figure 6. Functional Block Diagram of OCC Omega Data Processor

detectors which are driven by reference frequencies equal to the specified tone input frequency. The only difference in the synchronous detectors is that the reference frequencies for the two detectors are 90 degrees out of phase. As shown in Figure 6, the outputs of the synchronous detectors are applied to analog integrators which have time constants of approximately one second and output noise bandwidths of approximately 1 Hz. The outputs of the analog integrators represent the sines and cosines of the Omega input tones (relative to the reference tones). These sine and cosine outputs are applied through analog multiplexer switches to an analog-to-digital converter where the analog signals are converted to digital representations of the platform Omega tone phases. The encoded platform Omega phase data is then stored in the OCC digital computer memory for further processing.

A significant feature of the OCC Omega processor is that the Omega tone phase measurements are made open-loop. That is, phase-lock loops are not required for the phase measurements. The advantages offered by this open-loop phase measurement technique are:

- Zero acquisition time is required because of the absence of the phase-lock loops.
- Residual phase errors can be eliminated without continuous tracking of the Omega tones.
- An arbitrarily low noise bandwidth can be achieved by further integration in the digital computer.
- Frequency errors on the Omega tones can be accommodated.

The digital computer processing of the encoded Omega phase data involves three basic tasks. First, the computer must measure and compensate for any frequency errors (doppler shift frequencies) on the Omega tones. Second, it must average the tone phase values over approximately a three-minute time period to obtain useful signal-to-noise ratios. Third, the OCC Omega data processor must compensate for the small differences in transmission times of each tone from the various Omega transmitters. The OCC computer processing of the Omega data is described in more detail in "Design Study Report for Omega Position Location Equipment Control Center," Report No. 3-815800-3, Texas Instruments Incorporated, 14 October 1966.

E. OMEGA SYSTEM DESCRIPTION

The Omega Navigational System was developed at the Naval Electronics Laboratory with assistance from several other organizations including the Harvard

Cruft Laboratory and the Naval Research Laboratory. Evolution of the Omega system followed an extensive investigation of very-low-frequency (VLF) propagation characteristics throughout the last decade. One result of these investigations has been to show that the 10 kHz region of the VLF spectrum has a very low attenuation rate and exhibits exceptional phase stability. These characteristics permit worldwide propagation of radio waves and allow phase measurements with an rms variation of less than five microseconds. Within this frequency range the radiated energy is propagated as a guided wave in the space between the earth and the reflecting ionosphere with an attenuation rate of nearly that due to inverse spreading loss. Near the transmitter interference between the ground wave and the single-mode guided wave transmission cause phase shifts of considerable magnitude. Beyond a few hundred miles the single-mode propagation dominates and the signal can be used for position measurements up to a distance of at least 5000 miles from the transmitter. Frequencies between 10 and 14 kHz were chosen for use with Omega because of the high excitation of the first mode and the low interference effects at sunrise and sunset of the higher mode.

The optimization of the Omega frequencies with respect to the above characteristics of the transmission medium has been verified by experimental results. The experimental phase of the Omega program is essentially completed and an overall operational design of considerable flexibility has been established and is being implemented. The Omega Project Office, under the Chief of Navy Material, has been established to direct the construction of the entire Omega network. Three pre-operational stations have been constructed and are providing coverage over the northwestern quadrant of the earth. The complete Omega network could be operational by 1976 with the construction of eight operational stations.

The operational Omega System will consist of eight VLF transmitting stations each radiating 10 kilowatts of power, with an average separation between stations of about 5000 nautical miles. Each station will transmit, in time sequence, three frequencies, 10.2 kHz, 11.33 kHz, and 13.6 kHz that are harmonically related to a precise frequency standard. In addition, each station may be assigned a unique transmission frequency that will permit station identification. Figure 7 presents the Omega signal frequency and timing format. The letters A through H identify the transmitting stations. Blank timing intervals would be used for station identification transmissions.

It is expected that all eight transmissions will be receivable at nearly every point on earth and that at least five of the eight will produce usable signals with only a short monopole receiving antenna. The Omega receiver measures the relative phase of the signals from at least two pairs of stations, i.e., three transmitters. Two lines of position (isophase contours) are generated by the phase difference between each of the two transmitter pairs and the position of the receiver is established by the intersection of the two isophase hyperbolic contours. The very long base lines between stations results in position lines that diverge only slightly and that cross each other at nearly right angles. This geometric excellence, along with the high degree of phase stability and low attenuation rates of VLF radio signals, results in a reliable system with good absolute accuracy that varies little with geographical position.

The uncertainty in an Omega line of position can be summarized as one standard deviation of about three-tenths of a mile over a daytime propagation path and about twice that at night. By the time the Omega network becomes operational, it is expected that the rms fix error, for all causes combined, will be about one mile in the daytime and two miles at night. In recent tests performed by the Naval Research Laboratory, the rendezvous or station keeping accuracies attained were around 200 yards. Thus, a fixed station can provide very accurate relative position measurements (and velocity measurements through continual tracking) of platforms over a large area.

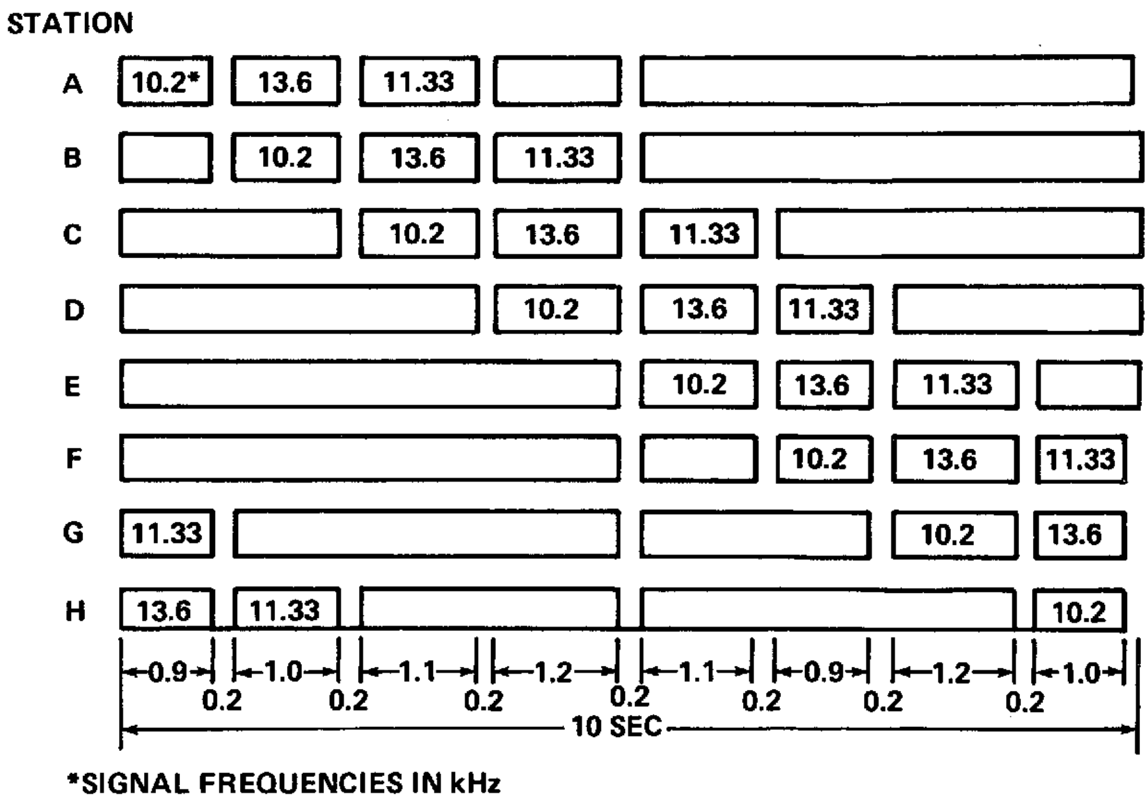

Figure 7. Omega Transmitted Signal Time and Frequency Format

Hyperbolic Navigation Technique

At any locus on the earth's surface there will be a fixed phase angle difference between the signals received from a pair of stations transmitting on a common frequency. This line of constant phase difference (isophase line) is represented by a hyperbola. An Omega receiver measures the relative phase of signals from at least two pairs of stations, i.e., three transmitters. Two lines of position (LOPs), isophase contours, are generated by the phase differences between each of two transmitter pairs. The position of the receiver is established by the intersection of these constant phase difference contours.

Receiver motion causes the phase angle difference to change. Therefore, when the receiver moves a distance equal to one-half wavelength of an Omega frequency, the phase difference reading changes by one cycle (360 electrical degrees). The LOPs separated by one cycle define a lane the difference measurements of which are repetitive from lane to lane leading to ambiguities in position determination that must be resolved.

Because the three Omega transmitted frequencies are derived from a common frequency standard, their phase relationships are very stable. Thus, the phase differences between the transmitted signals can be used to define lanes of increased width. For example, the 1.13-kHz phase obtained by taking the difference between the 11.33-kHz and 10.2-kHz phases can be used to define a lane width of 72 nautical miles on the baseline between two stations.

Initially the Omega System was to have lower frequency tones modulating the three transmitted tones. Use of these modulating tones would allow lane widths of up to 8000 miles to be obtained. However, this aspect of the Omega System will not be implemented. Other methods that are used to resolve lane ambiguities are lane counting from an initial lane of known location and occasional dead reckoning position determination using other navigational techniques.

In the operational Omega System the use of long baselines and the worldwide distribution of stations will ensure that lane widths that exhibit little spreading will be available at any location on the earth's surface. Off the baseline between a pair of stations, the hyperbolic LOPs begin to diverge from each other, leading to increasing lane widths. It can be shown that the lane width at any receiver position is proportional to the cosecant of one-half the angle between the two stations, as measured from the position. The calculation of the angle is performed using spherical trigonometry where all the distances are measured in arcs of great circles. Thus, as the receiver moves farther off the baseline, a given error in determination of phase difference corresponds to an increasing error in determining position location.

Skywave Correction Factor

Omega receivers use the skywave component of the propagated VLF energy in measuring the phase difference between transmissions from two stations. The skywave phase velocity is a function of many parameters, and its magnitude between the transmitter and any location varies with the time of day, and the day of the year. To accommodate these variations in phase velocity, a skywave correction scheme is employed.

Charts are published with LOPs corresponding to a theoretical skywave phase velocity. Tables are published containing skywave correction factors that are a function of transmitter location, receiver location, hour, and day, and are to be added to or subtracted from Omega chart LOPs. These correction factors are determined from the magnitude by which the theoretical phase velocity differs from the true phase velocity. They are calculated with equations based on phase measurements taken over a period of years at various locations.

At present, skywave correction factors are published for 10.2 kHz and 3.4 kHz. The uncertainty in the skywave correction factor is one of the major sources of error in the Omega System. Unpredictable perturbations in the VLF propagation velocities are another source of error.

Differential Omega

The differential Omega technique is used to overcome the uncertainty introduced into Omega position determination by the skywave correction factor. In this technique a monitor station is located at a fixed position where the coordinates are accurately known. The skywave correction factor for the location can be found from the published tables. At any instant the monitor station can determine the error between the phase differences of the received Omega signals and the values obtained from the correction table and charts. This instantaneous error can be broadcast to Omega users in the area who use it to correct their position determinations. The resultant position determination error of the user will be a function of the distance from the user to the monitor. If the distance becomes large, the skywave correction is inaccurate.

F. OMEGA LANE AMBIGUITY RESOLUTION

The position-location ambiguity in the Omega system, as now implemented results in a lane width of 72 NM which is clearly inadequate for GRAN. The simplest technical solution is that of adding low frequency modulation of 226-2/3 Hz, 45-1/3 Hz and 11-1/3 Hz to generate land width of 360 NM, 1800 NM and 7200 NM, respectively, to the existing three tones of 10.2 KHz, 11-1/3 KHz and 13.6 KHz. The above tones have already been suggested as low frequency modulation on the already existing three tones. Unfortunately, this solution is not feasible because of two reasons. First, the addition of low frequency modulation is prohibitively expensive as the cost will be about $10 million per station. Secondly, these tones would interfere with presently existing Omega receivers both in the United States and abroad.

To overcome this difficulty, it is proposed that the additional tones be derived in the same manner as the already existing tones (without modulation). This is feasible because the antenna bandwidth requirements will not change significantly and the cost of implementing this change is less than 100K per station. There are, however, difficulties with this system, i.e., fitting tones with certain constraints in restricted bands to guard against interference with existing Omega receivers.

This leads to the solution proposed below. It is proposed that the lane ambiguity be resolved for 360 NM and 1800 NM by adding of two tones and that the remaining ambiguity (over 1800 NM) be resolved by measurements of the relative signal strength from different stations. These techniques will now be described.

1. Signal-to-Signal Ratio Comparison

This method is based on the fact that the amplitude of VLF signals decreases in strength approximately inversely with distance. Preliminary computations indicate a location accuracy of ±300 NM at the baseline between Omega stations and ±750 NM at the furthest location from the baseline, which is certainly within the 1800 NM accuracy required. An understanding of this technique may be derived from the following example.

Consider a platform located at P some distance off the baseline of Omega stations A and B which might be some 5000 NM apart as shown in Figure 8.

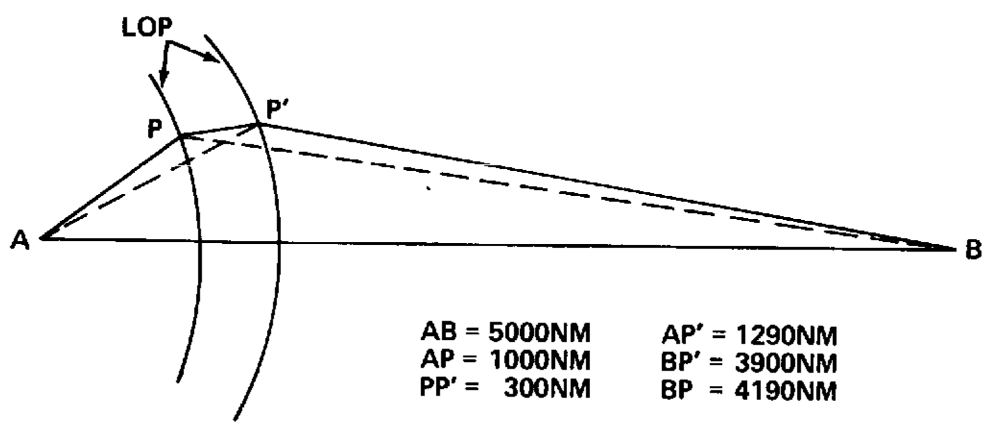

Figure 8. Comparative Signal Paths

In particular, consider the case where the platform, at position P is 1000 NM from A and 4190 NM from B. Let the platform be relocated by 300 NM to position P' in a direction perpendicular to the LOP so that position P' is approximately 1290 NM from A and 3900 NM from B. Referring to Figure 9 the signal from A then decreases by about 9 dB and the signal from B increases by about 7 dB.

Inspection of the 10 kHz curve in Figure 9 indicates that the change in signal strength per 300 NM (550 KM) is generally larger than 7 dB, an easily measureable quantity.

The two SNR's from A and B are first measured. Since the noise level is constant during the measurement the difference of the two signal-to-noise ratios in dB can be calculated and a Hyperbolic Line of Position obtained.

2. Additional Tones

The two additional tones can be implemented in two ways: either by transmitting two tones in the 10.2-11-1/3 kHz band or by utilizing two of the proposed timing and synchronization tones in the 11.5-13.6 kHz band with certain modifications.

The two proposed tones are 10.880 kHz and 10.774 kHz producing lane widths of 360 and 1800 nautical miles, respectively. These tones can be easily generated in the frequency synthesizer of the Omega station by frequency division techniques. Furthermore, the differences of these tones from others result in 226-2/3 and 45-1/3 Hz, respectively, which are proper submultiples of the already existing difference tones. (This implies that the new lanes contain an integer number of smaller lanes.) These tones lie in the allowable 230 Hz band (10,700 Hz - 10,933-1/3 Hz) thus satisfying the non-interference requirement. Preliminary discussions with the Omega Office indicate that the Omega Office is very receptive to our problem and they will make an effort to satisfy our requirements within their financial means and authority.

3. Multiple Lines of Position (MLOP)

This technique would employ the well known iterative estimation process called Kalman Filtering and would utilize the redundant lines of position generated by signals from four or more OMEGA stations. It may be seen in Figure 10 that three LOP's intersect perfectly only at the true location. At present only four OMEGA stations are interim operation; by 1975 eight will be in operation, providing global coverage. Some preliminary results have already been obtained which indicate that the MLOP technique is feasible.

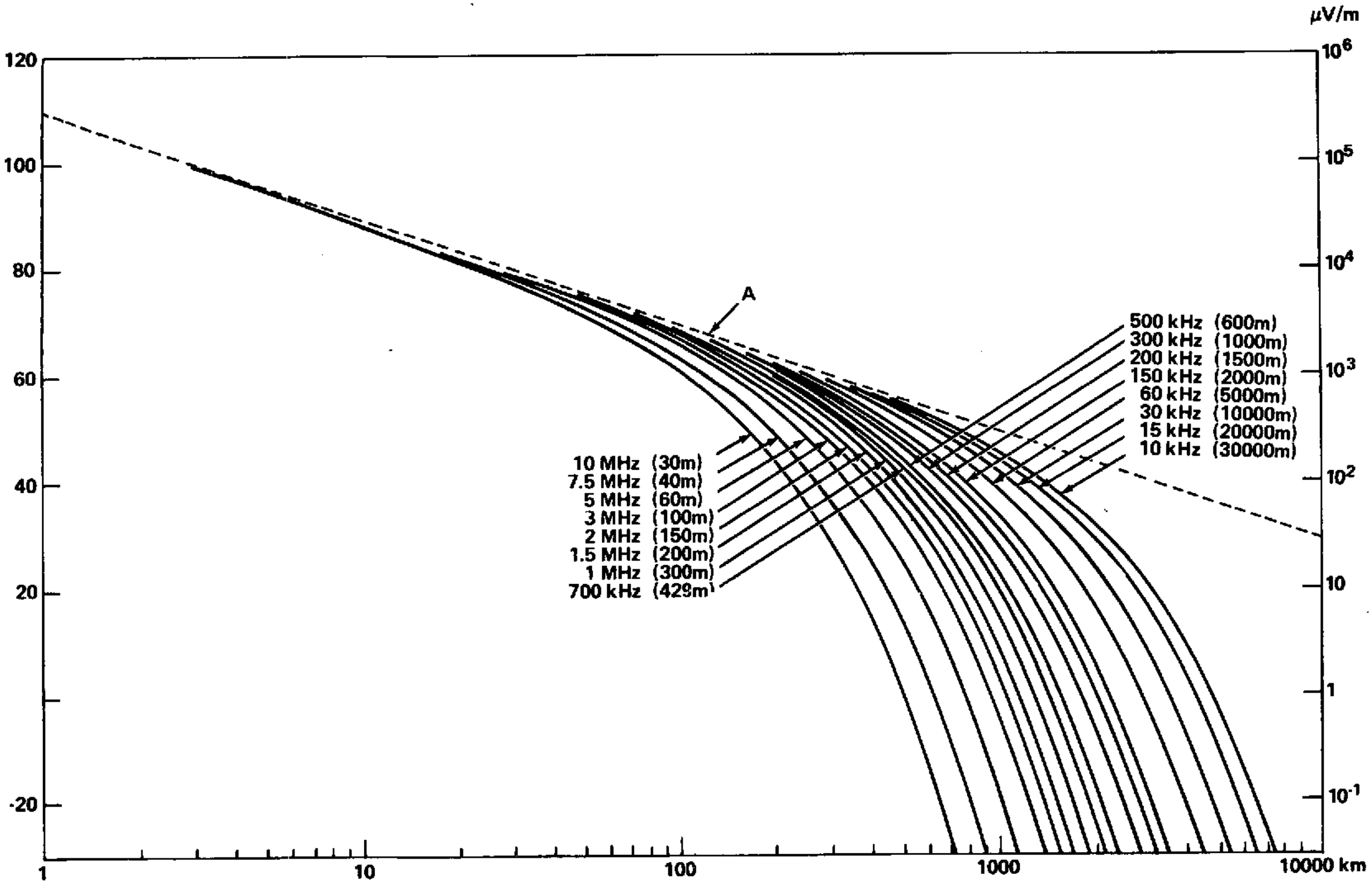

Figure 9. Ground-wave Propagation Curves

Sea, $\sigma = 4$ mho/m, $\epsilon = 80$; A: Inverse distance curve

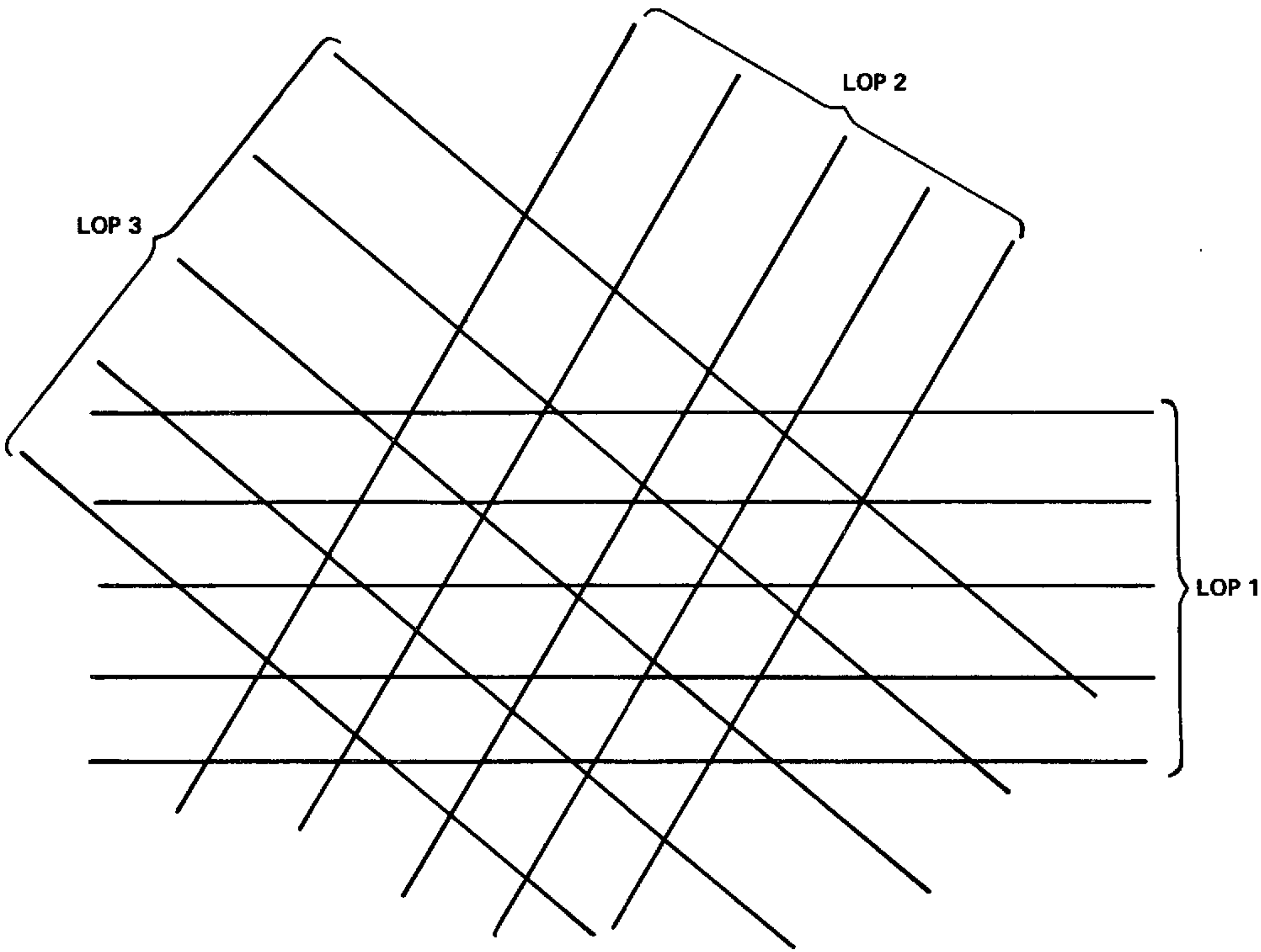

Figure 10. Geometry of Redundant Grid Points

4. Time of Arrival

This technique uses the whole waveform transmitted by the OMEGA stations. The effect is that the ambiguity frequency is 10 seconds, the repetition period of the OMEGA transmission. The signals from the two (2) OMEGA stations could, in concept, be cross correlated to obtain the difference in time of arrival; however, the required level of quantization is not practically achievable in view of the magnitude of the ambient noise. To overcome this problem the configuration of Figure 11 is used. A calibration platform is located in the vicinity of OMEGA station A. The signal from station A is transmitted to the satellite through two paths, the calibration platform and the platform P. The cross correlation of these two signals is maximized to obtain the difference in time of arrival τ_1.

$$\tau_1 = t_{p1} + t_s - t_{c1} - t_1$$

Where the above parameters are shown in Figure 11, t_{c1} and t_1 are known and τ_1 is measured by the correlation technique.

Similarly for the signal from OMEGA station B the difference in time of arrival of the signal throughout the platform P and the calibration platform P is

$$\tau_2 = t_{p2} + t_s - t_{c2} - t_1$$

where t_{c2} and t_2 are known and τ_2 is measured by auto correlation techniques; subtracting τ_2 from τ_1

$$\tau_1 - \tau_2 = t_{p1} - t_{p2} + t_{c2} - t_{c1}$$

or

$$t_{p1} - t_{p2} = \tau_1 - \tau_2 + t_{c1} - t_{c2}$$

the right hand of the equation is either measurable or known.

Dividing by the propagation velocity we obtain

$$x_{p1} - x_{p2} = \text{Constant}$$

where x_1, x_2, are the distances of the platform from A and B.

The above equation indicates a hyperbolic line of position with no ambiguity. Obviously this technique requires less than eight calibration platforms.

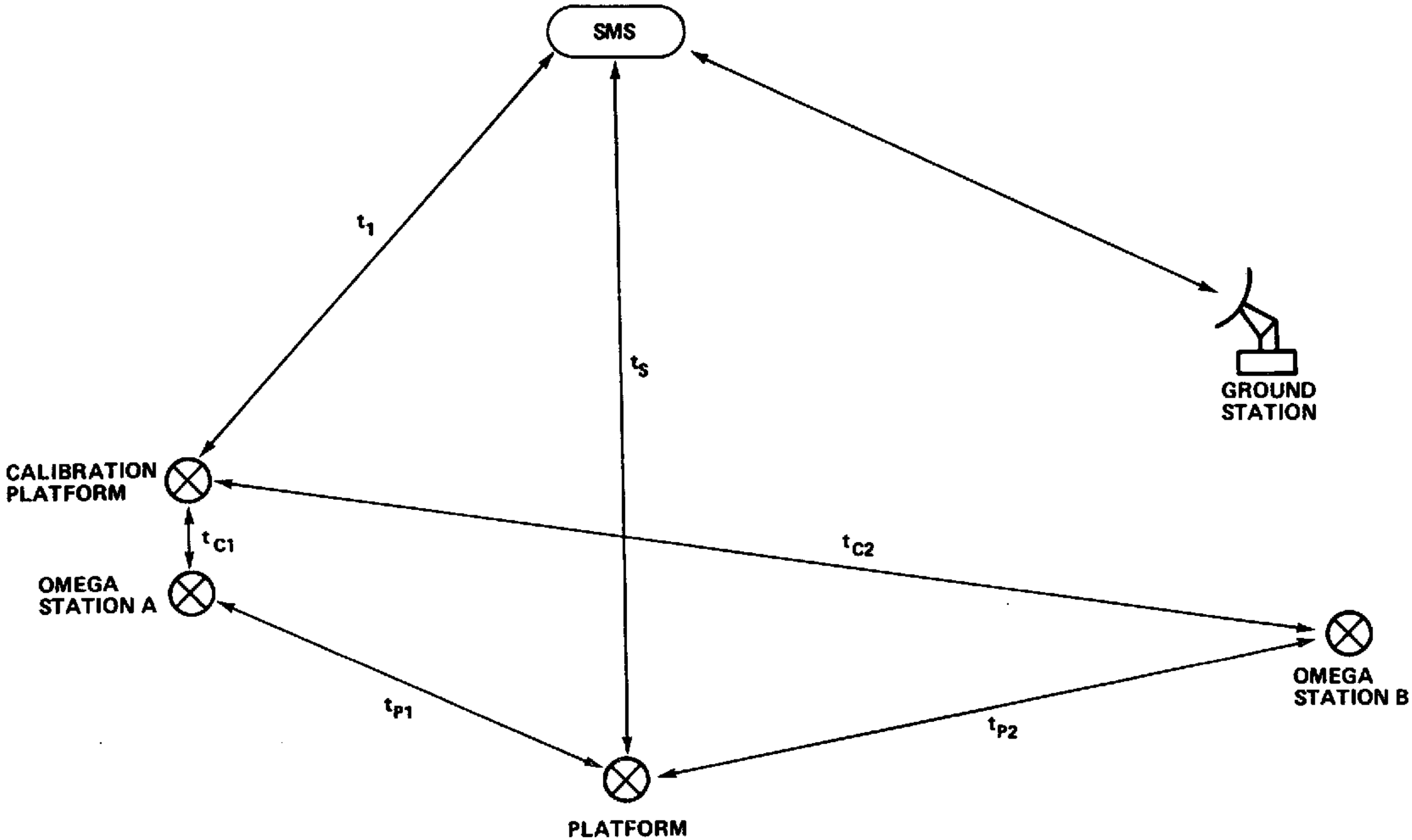

Figure 11. Signal Paths

V. SATELLITE/GRAN COMPATIBILITY

The ground rules to be followed in the design of the GRAN system will stress compatibility with the synchronous satellite facilities to the greatest extent possible. The major areas of concern are the following:

1. Bandwidth utilization
2. Return link i-f interface and stability
3. Transponder scheduling
4. Carrier frequency

Transponder scheduling will require allocation of the satellite for periods of approximately 30 minutes. This should allow time for transmission, computation and retransmission of locational coordinates, and provide a reasonable margin. As the experiment progresses, this period will be reduced to the minimum possible. The selection of center frequency within the transponder bandwidth must be determined by NASA personnel. At the 1971 WARC meeting in Geneva the band from 406.0 to 406.1 MHz was dedicated to worldwide satellite SAR. In the next major phase of the GRAN experiment efforts will be made to develop equipment at the SAR frequency on a NASA application satellite.

VI. LINK CALCULATIONS

As shown in Figure 1, the system consists of a central ground facility, the geosynchronous satellite and remote platforms. The platforms will be deployed over the coverage area of the satellite encompassing depression angles from 5 to 90 degrees. Communication from the platform is at UHF, at the frequency of 406.0 to 406.1 MHz. Communication to the ground station is at SHF. The system design will provide for up to 25 simultaneously transmitting platforms.

A. SARCOM TO SATELLITE TO GROUND

The calculations for the SARCOM-to-satellite portion of the reporting link are shown in Table 2. It is seen that the carrier-to-noise density ratio at the input to the transponder is 35.7 dB/Hz and 31.0 dB/Hz for the high and low depression angle platform, respectively.

The carrier-to-noise density ratio calculated for the satellite-to-ground station portion of the reporting link is expected to be at least 50 dB/Hz. Since this is over 14 dB greater than the highest carrier-to-noise density ratio for the UHF uplink of 35.7 dB/Hz, the degradation is at most 0.1 dB. It will, therefore, be assumed that the resulting carrier-to-noise density ratio on the ground is at least 31.0 dB/Hz for up to four reporting platforms.

B. A/R TONE ACQUISITION AND TRACKING

The calculation of margin attainable at the ground station for the 5^{o} to 45^{o} and 45^{o} to 90^{o} depression angle platforms are shown in Table 3. The margins apply to the A/R tone only during acquisition and tracking. The C/KT received at the satellite can be assumed at the ground in accordance with the preceding paragraph. Allowing an 8 dB S/N margin for 99% probability of lock, the acquisition bandwidth becomes prime factor insofar as the margins are concerned. Since a 5 to 6 dB margin is desired, the receiver PLL bandwidth is in the order of 50 Hz. Threshold extension techniques will be investigated for possible reduction in acquisition time.

C. SARCOM DIGITIZED DATA

In a similar manner to that described in Section VI calculation of the margins attainable during demodulation of the received platform digitized sensor data were accomplished and are shown in Table 4.

Table 2
Link Calculation (Reporting Link)
SARCOM to Satellite*
Frequency: 406.0 MHz

	High Dep. Angle (45-90)	Low Dep. Angle (5-45)
Transmitter Power	7.0 dBw	7.0 dBw
SARCOM Feed and Line Loss	-0.5 dB	-0.5 dB
SARCOM Antenna Gain	0.0 dB	0.0 dB
Free Space Loss	-176.1 dB	-177.9 dB
Polarization Loss	0.2 dB	-3.0 dB
Satellite Antenna Gain (min. req.)	8.0 dB	8.0 dB
Satellite Feed Loss	-1.6 dB	-1.6 dB
Satellite Off-Beam-Center Loss	-2.4 dB	-2.5 dB
Boltzman Constant	228.6 dBw/Hz	228.6 dBw/Hz
Satellite Noise Temp. (516^{o}K)	-27.1 dB	-27.1 dB
Reporting Uplink C/KT	+35.7 dB/Hz	+31.0 dB/Hz

*These calculations subject to modifications pending approval of the additional tones.

Table 3

A/R Tone Margins

		Tracking	
	Acquisition	Data Mode	Omega Mode
Link Pr/KT (Low Dep. Angle)	+31.0 dB/Hz	+31.0 dB/Hz	+31.0 dB/Hz
A/R Tone Share of Output Power	0.0 dB	-6.0 dB	-10.0 dB
Required C/N for 99% Probability of Lock	-8.0 dB	-8.0 dB	-8.0 dB
PLL Receiver Bandwidth	-17.0 dB (50 Hz)	-10.0 dB (10 Hz)	-10.0 dB (10 Hz)
Margin (High Dep. Angle)	9.8 dB	10.8 dB	6.8 dB
(Low Dep. Angle)	6.0 dB	7.0 dB	2.2 dB

Table 4

Digitized Data Margins

Link Pr/KT (Low Dep. Angle)	+31.0 dB/Hz
Data Signal Share of Output Power	-1.2 dB
Required C/N (PSK)	-9.7 dB
Bandwidth (70 Hz)	-18.5 dB/Hz
Margin (High Depression)	+5.4 dB
(Low Depression)	+1.6 dB

D. OMEGA SIGNALS

The minimum acceptable Omega signal-to-noise power ratio at the platform receiver is specified as 0 dB in a 1 Hz bandwidth. It is assumed that the VLF noise density is constant across the VLF receiver band. It is further assumed that all but 10% of the platform output power is contained in the three tone bands (each 100 Hz wide). The Omega tones and associated VLF noise power are therefore contained in a total bandwidth of 300 Hz. Using the values in the report, "OPLE System Power Budget," and calculating, the degradation of approximately 1 dB results. This may be recovered by either increasing platform transmitter output power or increasing the number of Omega samples taken. Neither option adversely affects the objectives of the GRAN experiment if implemented. However, it is doubtful that such action will be required.

VII. PROGRAM PLAN AND SCHEDULE

A. MANAGEMENT

The period of activity for the experiment is logically divided into two phases. The first is the study and development and testing of hardware and software equipment. The second is the field operational testing, followed by analysis and reporting of findings. The first phase has been primarily the responsibility of GSFC with the NAVAIRTESTCEN and USCG providing support in the generation of SAR specifications concerning hardware size, weight and configuration and processing requirements. Technical support will also be rendered by NAVAIRTESTCEN and USCG through attendance at design reviews.

The second phase will be primarily the responsibility of USCG and NAVAIRTESTCEN and will consist of providing necessary plans, personnel, equipment and facilities for carrying out testing around the globe. The analysis and reporting of results will be a cooperative effort between the respective agencies. Upon completion of the experiment, it will be the responsibility of the USCG to pursue the operational aspects of a future system through cooperation with various SAR agencies.

B. RESPONSIBILITIES

Coordination between NASA, other government agencies or special groups as needed to obtain authorization for use of a synchronous satellite will be the responsibility of NASA Headquarters. The detailed responsibilities of the GRAN experiment could be as follows:

GSFC:

1) The study, design, test and operation phases of the GRAN experiment.

2) Technological aspects of the experiment including interface between GRAN and the synchronous satellite and processing and documentation of data.

3) Delivery of prototype platform units to NAVAIRTESTCEN in accordance with mutually agreed upon specifications.

4) Assisting other investigators in administration and coordination of experiment.

5) Participating in and coordination of publications relating to the experiment.

NAVAIRTESTCEN:

1) Providing support in the development of the system design.

2) Generation of detailed operational plan for, and conduct of, field tests.

3) Analysis and interpretation of data.

4) Participating in and coordination of publications relating to the experiment.

The U.S. Coast Guard:

1) Providing support in the development of the system design.

2) Generation of detailed operational plan for, and conduct of, field tests.

3) Analysis and interpretation of data.

4) Participating in and coordination of publications relating to the experiment.

5) Pursuing the operational aspects of a future system through cooperation with various SAR agencies under the auspices of the National SAR Plan.

C. TASK/MILESTONE SCHEDULE

Tasks and milestones are shown in Figure 12 and pertain to study, design, fabrication, testing and evaluation and the operational phases. The work is divided into four major categories. These are:

1) Study and design
2) Hardware development
3) Operational testing
4) Data analysis

The work to be accomplished under the major categories is as follows:

<u>Study and Design</u>

The study and design work will consist of the following subtasks:

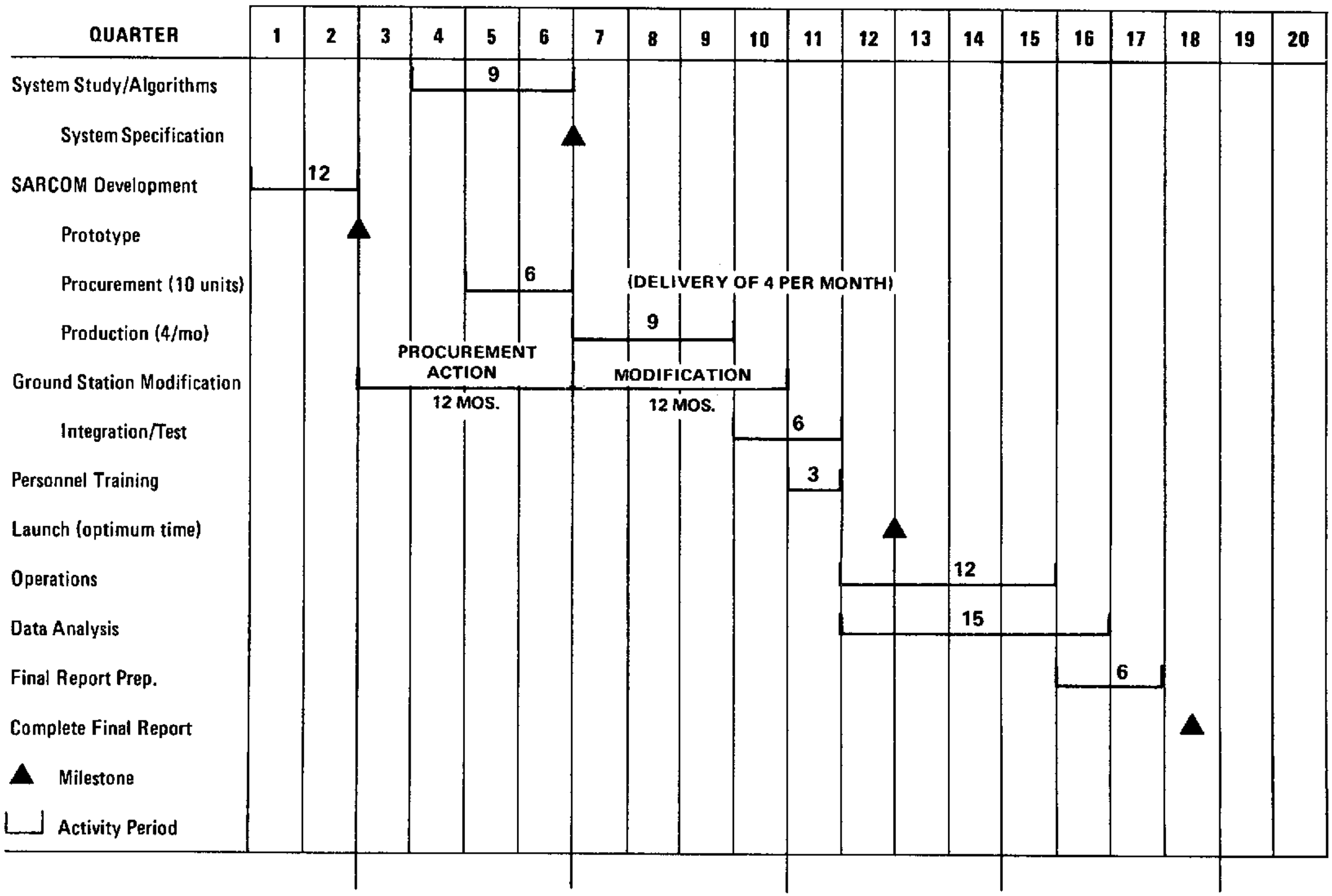

Figure 12. Milestones and Schedule

1. System Engineering

   a. Analytic calculations necessary to identify the detail system parameters.

   b. Identification and specification of major system interfaces.

   c. End-to-end system performance specifications.

   d. Subsystem performance specifications.

2. Processing Algorithms

   a. Hardware/software tradeoffs.

   b. Lane ambiguity resolution study and processing requirements.

   c. System software simulation.

3. Supporting Studies

   a. Improved platform VLF receivers.

   b. Differential Omega.

   c. Skywave correction improvement.

The total effort will require 12 months for completion; however, specifications and interfaces needed to begin ground station design and final platform design will be sufficiently detailed within the first six months. The final months of the study and design will coincide with ground station and platform development contracts described below.

Hardware

a. Platform Prototype—A contract was let in August 1971 with the General Instrument Corporation of Hicksville, L.I., N.Y., for development of a prototype Advanced OPLE platform. The effort was completed in June 1973 under the NASA Advanced OPLE SRT program. The design is a representative GRAN SARCOM package, and is configured in accordance with SAR specifications detailed in this proposal. Emphasis is placed on reproducibility as well as small size and weight.

b. Ground Station—Upon approval of the experiment, procurement action will be initiated for Ground Station modifications and improvements. The effort will mainly consist of implementing the processing algorithms developed under the study program. A significant level of interface between the respective contractors' efforts is therefore required. The new ground station design will feature random access capability, real-time data processing, and advanced input signal acquisition and extraction techniques. A significant level of system testing will be carried out prior to shipment of equipment. However, final testing and operator training will be completed at the installation site.

c. Platform Production—A procurement action will be initiated for the platforms. Bids will be solicited on a competitive basis.

Operational Testing

System testing will begin at ground station contractor's site using the prototype platform and modified station equipment before launch. Final testing must be conducted at the station installation site. Five to six months of checkout is planned, as shown in Figure 12, prior to commencement of experimental operations. A satellite simulator will be designed into the ground station.

Data Analysis

Analysis of engineering and system performance data will form an integral part of the experiment throughout all operational phases. Daily log sheets, computer printout, and magnetic tape will be used to store data. Support from contractors will be used in system evaluation. NASA, NAVAIRTESTCEN and the USCG share equal responsibility in the analysis and reporting; a final experiment report will be coauthored.

Figure 12 describes the tasks to be completed at each of the selected test sites. These efforts will begin following system testing, and will require 12 months to complete. A minimum of 500 independent transmission sequences are required for sufficient statistical data at each site. This corresponds to 5 hours of satellite operating time; five working days are allocated for collection of this data. Following the engineering test sequences, two weeks are allocated for practice SAR missions. The exact nature and duration of the SAR missions will be defined and reviewed with the cooperation of SAR agencies prior to operations.